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The Great Salt Lake Causeway—A Calculated Risk Revisited

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SYNOPSIS: The construction of the Great Salt Lake Causeway involved several calculated risks. Original design assumptions on lake level and consolidation settlement were not realized, creating a unique situation where the critical time for stability of this embankment was not necessarily at the end-of-construction. Along more than half of the Causeway's 12-1/2 mile length, consolidation and strength gain has apparently been inhibited by a layer of salt. Because it was anticipated that calculated Factors of Safety for current conditions would be close to the 1.0 originally used, a comparative approach to stability evaluations was adopted. In this approach, Factors of Safety calculated for known, past stable conditions were compared with those predicted for future conditions. Judgements of future Causeway stability were made by comparing Factors of Safety with time. The presence of a salt layer in the foundation of a portion of the Causeway's length renders exact solution of stability intractable to usual analytical procedures.

INTRODUCTION

In his 1964 Terzaghi Lecture, Casagrande (1965) described the design and construction of this 12-1/2 mile long embankment across the deepest portion of the Great Salt Lake, location indicated in Figure 1, as an outstanding example of a calculated risk. Completion of the Causeway in 1959 required the application

of considerable engineering judgement as the original design of the embankment underwent several empirical modifications based on the results of test fills and on actual construction failures. Initial "assumed" risks included;

1. Use of a design Factor of Safety close to 1.0, for expected greater economy of a less conservative design, but accepting the increased risk of failures.
2. Selection of crest elevation 4212¹, based on lake levels over the previous 30 years and the anticipation that there was a general downward trend to the level of this terminal lake, see Figure 2. This crest elevation was more than 6 ft. lower than the rails on the 55 year old timber trestle that it was to replace.
3. The expectation that consolidation of the soft foundation clays would be on the order of 4 to 8 ft., and that this would occur within several years of construction, thus yielding a steady increase in stability.

However, the level of the Great Salt Lake, a lake with no natural outlet, has fluctuated nearly 20 ft. since 1959, see Figure 2. Recent historically high lake levels and continuing Causeway settlement due to foundation clay consolidation, also illustrated in Figure 2, have forced Southern

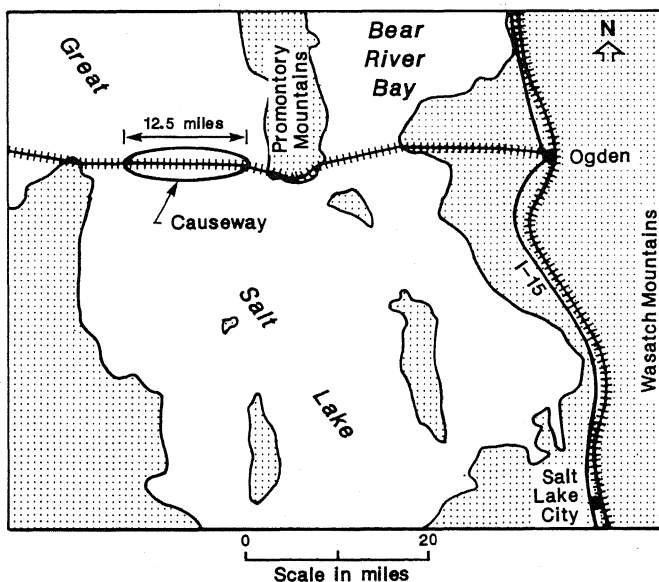


Figure 1. Location of the Great Salt Lake Causeway.

¹ All Elevations refer to Southern Pacific's Hood's Datum, and are therefore 3.4 ft. above elevations based on USGS datum.

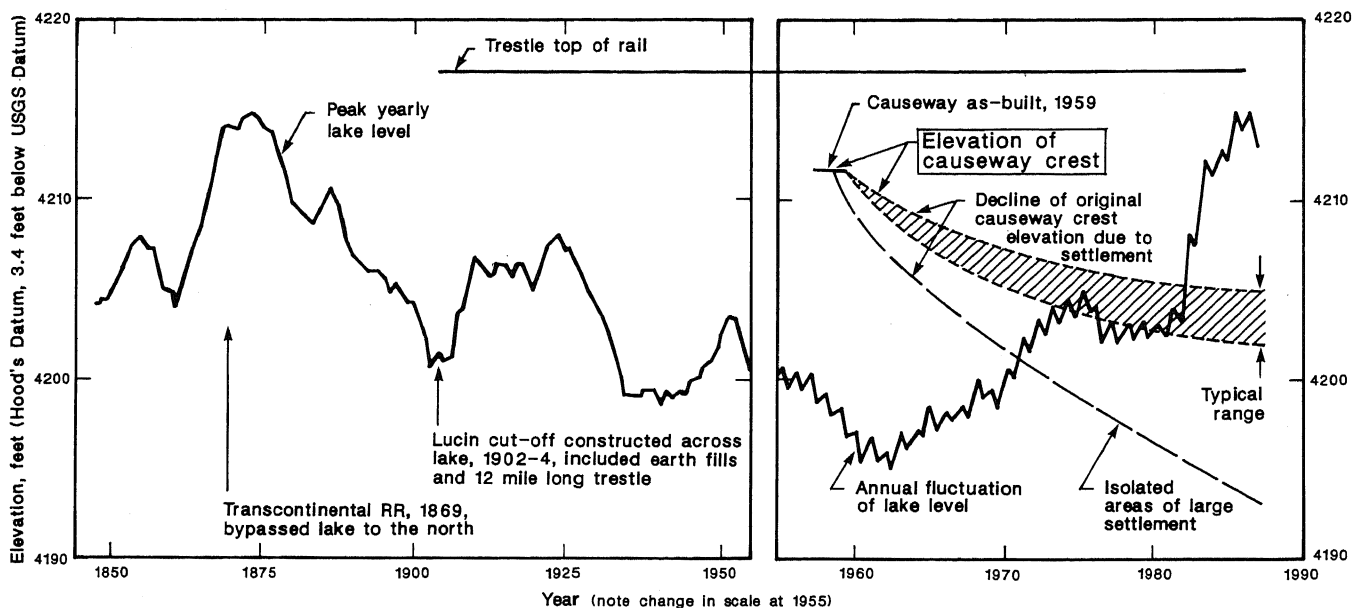


Figure 2. Levels of the Great Salt Lake and Causeway Crest.

Pacific railroad to add significant amounts of fill to the crest to maintain adequate freeboard. Filling has increased stresses on the foundation clays and necessitated re-assessment of Causeway stability. Studies have shown that a unique situation has developed wherein the end-of-construction condition was not necessarily the critical time for stability.

A comparative approach to stability assessments was adopted in which the Factors of Safety were calculated at selected cross-sections for differing conditions that existed at various times since construction. Changes in Factor of Safety from those calculated for past, stable conditions were then evaluated to assess present and future stability.

Although stability was found to have improved where the Causeway is directly founded on a clay foundation, the presence of a brittle salt layer beneath much of the Causeway's length renders stability calculation by "usual" procedures intractable. Assessment of stability in these areas still requires engineering judgement, thus continuing the calculated risks.

SUBSURFACE CONDITIONS ALONG THE CAUSEWAY

Although the Great Salt Lake basin has in places over 7,000 feet of sediment, only those strata within 150 to 200 feet of the present mudline were of consequence to Causeway stability. Below that level, stiff dessicated clay from an evaporative lake cycle is present. The overlying sediments are predominantly soft, plastic organic clays that exhibit brittle behavior in compression tests,

Casagrande (1959). Fine sand partings are found in deeper strata of the soft clays.

Of particular importance to Causeway stability is a stratum of Glauber's Salt. It is present in the deeper lake areas and is buried under about 25 ft. of the very soft sediments. This hydrated sodium sulfate was deposited during the evaporative aftermath of Lake Bonneville. The stratum contains a wide variety of salt compositions, each separated from the next by clay seams, as described by Eardley (1962). The Glauber's Salt increases in thickness from west to the east, being less than 1 ft. thick along the western 2-1/2 miles of the Causeway, up to 20 ft. beneath the central 6 miles, and as much as 45 ft. thick near the east side.

To evaluate soil shear strengths required for the recent stability studies, an extensive program of soil sampling and laboratory testing was undertaken in 1984. Borings were made at five different locations both through the centerline of the embankment and over-water through the counter-weight berms. Because SHANSEP procedures (Ladd and Foott, 1974) were used to assess clay shear strength, over 100 consolidation tests were performed to determine profiles of maximum past pressure.

The stress profiles shown in Figure 3 indicate that far less consolidation has occurred in clay overlain by the salt. This was an important discovery, because shear strength increase would be similarly less than where the salt is present. The Glauber's Salt stratum has apparently inhibited drainage from the underlying foundation clays. Thus less than 35 percent of the eventual consolidation has occurred in most salt areas.

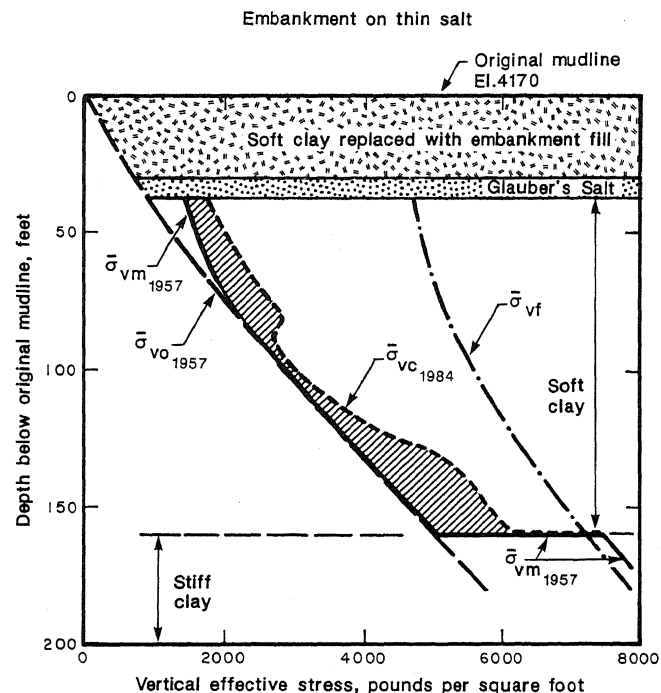
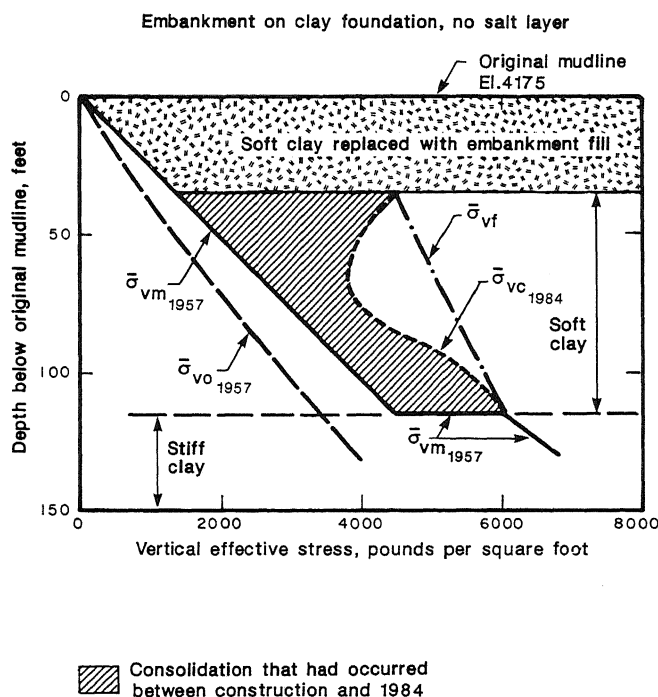


Figure 3. Stress Profiles Indicating Consolidation Since Causeway Construction.

- where: $\bar{\sigma}_{vo} 1957$ = preconstruction vertical effective stress
- $\bar{\sigma}_{vm} 1957$ = preconstruction maximum past pressure based on consolidation tests
- $\bar{\sigma}_{vc} 1984$ = vertical effective stress in 1984 (equals $\bar{\sigma}_{vm} 1984$ where $\bar{\sigma}_{vc} 1984$ is greater than $\bar{\sigma}_{vm} 1957$)
- $\bar{\sigma}_{vf}$ = final vertical effective stress under Causeway centerline at full consolidation

ORIGINAL CONSTRUCTION

A plan of the completed Causeway circa 1959, a profile showing fill and salt thickness, and two typical cross-sections are shown in Figure 4.

Casagrande (1959 and 1965) and Newby (1980) describe the design and construction. In brief, the embankment was generally constructed to a 60 ft. wide crest that was 12 ft. above the average lake level. Side slopes of the earth and rock fill embankment were 2 horiz. to 1 vert. A key design element was the removal by dredging of 20 to 25 ft. of the softest lake bottom sediments from beneath the main body of the fill. Along much of its length, the main fill was placed on the

Glauber's Salt. Counter-weight berms were placed adjacent to most sections of the main fill. The depth and width of the dredged trench, and berm width and locations are shown in Figure 4.

During construction, test fills were constructed in each of the different foundation areas to provide insight on performance and to verify the design sections used because the design Factor of Safety was close to 1.0. Unexpected construction failures that occurred emphasized the fact that as-constructed stability was marginal. These failures resulted in several design revisions which became largely empirical, Casagrande (1965).

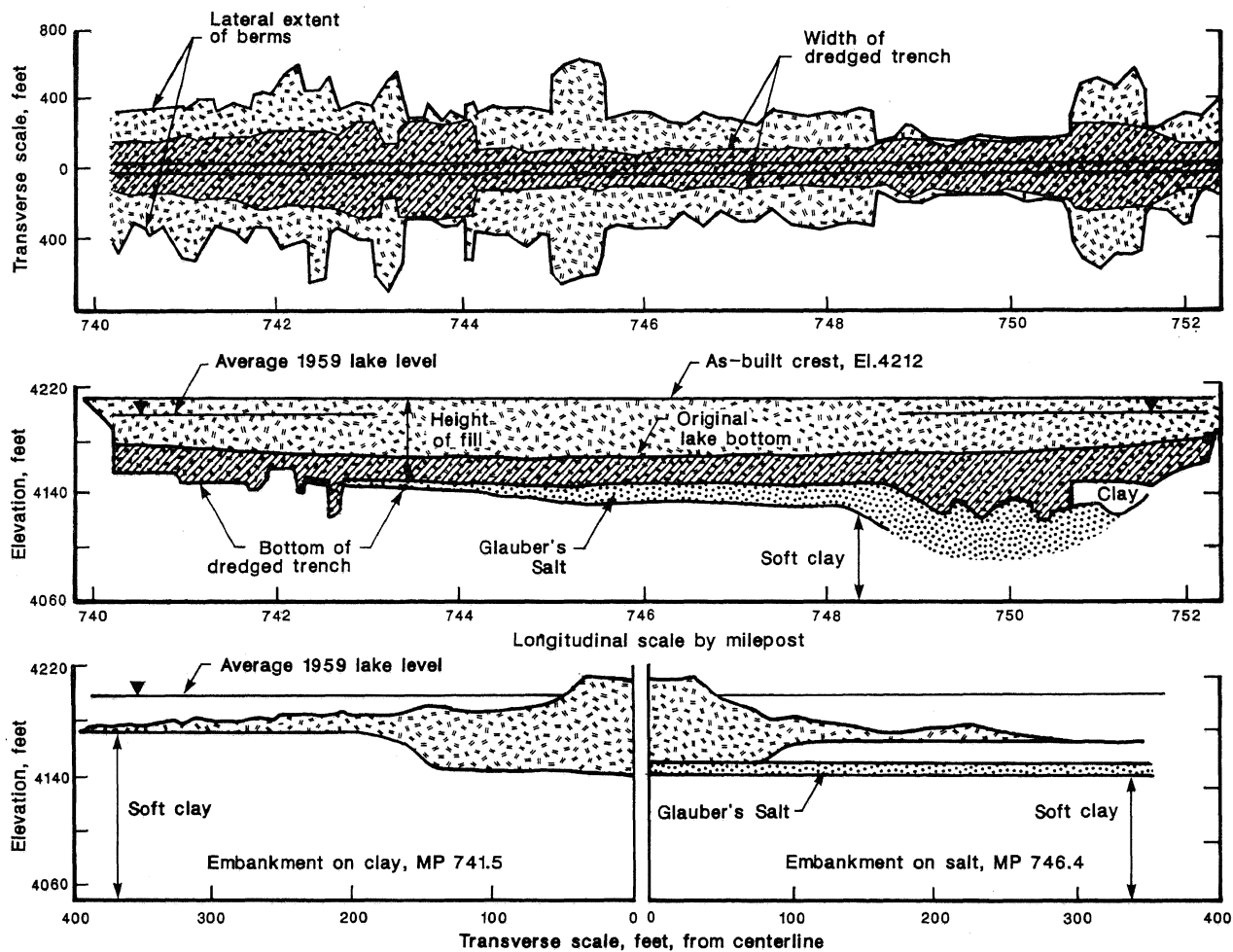


Figure 4. Plan, Profile, and Typical Cross-Sections of Causeway.

COMPARATIVE APPROACH TO STABILITY ASSESSMENTS

Unlike most embankments on soft ground, the critical time for Causeway stability was not necessarily at the end of construction. Falling and rising lake levels and the 12 to 25 ft. of fill added to the crest to accommodate settlement and rising lake level have caused changes in effective stresses on the foundation clays. Shear strength of the foundation clays has been very slow to increase in some areas.

In light of the above risks, a comparative approach was adopted for assessment of current and future stability. The Factors of Safety at the end of construction and other selected times since construction were calculated and compared. Judgements concerning stability were then made by comparing Factors of Safety for current and future conditions with those for past times when stable conditions were known to exist.

A few sections representative of the various constructed geometries along the 12-1/2 mile long Causeway were selected for detailed stability analysis. Stability analyses were made primarily for the West Side areas where the Causeway is solely on a clay foundation. These results and limited other analyses were used to temper judgements and assessments of instability risk where the stiff salt layer is present.

Stability analyses were made for the varying Causeway geometries, lake levels and shear strength profiles that were applicable to the past and present conditions at each section. Several possible future conditions were also analyzed to provide insight for the assessment of future risks of instability. The major changing conditions that were evaluated are listed in Table I.

The geometry of the Causeway surface was taken from cross-sections made at the end of

TABLE I. Changing Conditions Evaluated in Comparative Stability Analyses

YEAR	LAKE ELEVATION	ACCUMULATED SETTLEMENT	BASIS FOR CLAY STRENGTH (feet)	CAUSEWAY CONDITIONS/CHANGES
1959	4200	0	$\bar{\sigma}_{vm_{1957}}$	END OF CONSTRUCTION
1963	4195	2	$\bar{\sigma}_{vm_{1957}}$	MINOR SETTLEMENT
1969	4198	4	$\bar{\sigma}_{vm_{1969}}$ (INTERPOLATED)	FILL ADDED TO RAISE SUBGRADE BACK TO AS-BUILT (EL.4212), SOME BERM EROSION
1984	4210	7	$\bar{\sigma}_{vm_{1984}}$	FILL ADDED TO RAISE SUBGRADE TO EL.4214, BERM EROSION / ACCRETION
FUTURE	VARIED 4213 TO 4190	7	$\bar{\sigma}_{vm_{1984}}$	FILL ADDED TO RAISE SUBGRADE TO EL.4217

construction, and in 1966 and 1984. Settlement was distributed through the cross-section by assuming; 1. full settlement under the main body of the embankment, 2. no settlement under the berms, 3. linear variation in between. For perspective on the impact of "other factors" on instability risk, analyses were made for possible future lower and higher lake levels, addition or removal of fill from the crest, and berm thickness changes (field studies have indicated that erosion and accretion may have occurred).

Stability analyses were made using the Modified Bishop method for circular surfaces and Janbu method for non-circular surfaces, as available in the computer program STABLE, Boutrup (1977). A limited number of Morgenstern-Price analyses (ICES-LEASE) were performed which indicated Janbu to be approximately 10 percent conservative.

The shear strength of the foundation clays, both with depth and laterally from the main body of the fill, were determined by SHANSEP procedures for end-of-construction and later times. A stress ratio, $s_u/\bar{\sigma}_{vm}$, of 0.225 was established on the basis of laboratory undrained triaxial compression and extension tests and direct simple shear tests. The in-situ strength ratio was also estimated by back-analysis of two construction failures, which indicated somewhat lower values. A strength ratio of 0.20 was finally selected.

STABILITY OF EMBANKMENT ON CLAY

The section at MP 741.5 was evaluated because it is typical of "normal" West Side conditions where there is only clay in the foundation strata and did not experience a construction failure. The Factors of Safety calculated for this cross-section are summarized in Table II, as are the results of limited analyses for a cross-section at MP 747.6 where the salt layer is present.

The Factors of Safety calculated for conditions at the end of construction and four years later, when the Great Salt Lake was about 6 ft. lower, are essentially the same, and just slightly above unity. This agrees with design reports that the original design Factor of Safety was close to 1.0. The 1963 Factor of Safety was perhaps slightly higher than that calculated because some slight clay strength increase likely occurred, but was not considered in these analyses.

TABLE II. Calculated Changes in Factor of Safety with Time

YEAR	CALCULATED MINIMUM FACTOR OF SAFETY JANBU (NONCIRCULAR)	
	NON-SALT (MP 741.5)	SALT FOUNDATION (3) (MP 747.7)
1959	1.06	1.37
1963	1.04	(4)
1969	1.24	(4)
1984	1.25	(4)
FUTURE (1)	1.15	1.33
FUTURE (2)	1.25	1.37

1. SAME LAKE LEVEL AS 1984 CONDITIONS, CREST EL.4217.
2. LAKE LEVEL 3 FEET ABOVE 1984, CREST EL.4217.
3. SALT LAYER THICKNESS = 12 FEET, ASSUMED SALT SHEAR STRENGTH = 3600 psf.
4. NOT CALCULATED

The Factor of Safety calculated for 1969 conditions was 20 percent greater than original, a substantial improvement. This increased stability was primarily a consequence of increased shear strength in the foundation clay which more than offset the affect of the fill that was added to the crest in 1969 to compensate for 4 ft. of settlement that had occurred. The 1969 lake level was 2 ft. below 1959 level.

Calculations for 1984 conditions showed that the cumulative effects of continued foundation clay strength increase and lake level 10 ft. above the as-built level counteracted the destabilizing effects of the weight of an additional 6 to 7 ft. of fill placed on the crest in 1984 and the apparent erosion of about 2 ft. of material from the berms. The Factor of Safety was about the same as in 1969, about 20 percent greater than the as-built condition.

The effect of future changes in lake level, elevation of the crest, and erosion of the berms on Factor of Safety for Sta. 3550 were evaluated in a series of parameter studies. The results are shown on Figure 5 as change in Factor of Safety for each variable alone, the others being held constant at the 1984 conditions.

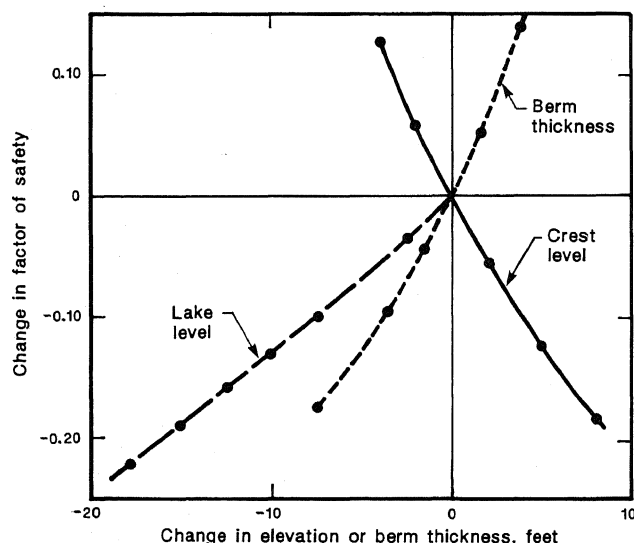


Figure 5. Effect of Various Parameters on Calculated Factor of Safety.

Changes in lake level were found to have about half of the effect on Factor of Safety as changes in either crest elevation or berm thickness. The direction of each effect is obvious. The Factors of Safety for two of the future conditions are included in Table II.

Based on these results, it was concluded that where there is only soft clay in the foundation, present and near-term, future Causeway stability would be greater than the as-built conditions. However, if lake levels recede below Elev. 4205, 5 ft. above the 1959 level, the calculated Factor of Safety would decrease to near the marginally stable values calculated for 1959 conditions.

PROBLEMS OF SALT OVER SOFT CLAY FOUNDATION

Stability calculations indicated that a working shear strength of the salt layer of between 10 and 25 times that of the clay at the same level was necessary for stability, i.e. Factor of Safety greater than 1.0. But it was not considered possible to make a meaningful analysis of Factor of Safety for the Causeway where the fill is on stiff salt over the soft foundation clays for the following reasons:

1. The salt is extremely heterogeneous, the spacing and frequency of clay seams varies with elevation and location.
2. The overall behavior of the salt is not understood, but is probably not adequately represented by laboratory compression tests on core samples.
3. The salt has probably experienced bending stresses due to differences in settlement between zones under the main body of the fill and beneath the lightly loaded berms, and compression due to the weight of the fill, but the effect of these changes on stratum strength is unknown.
4. There is strain incompatibility between the stiff, brittle salt and the soft clays below, although salt can typically accommodate large creep strains.

Limited comparative stability analyses were performed for insight on the magnitude of changes in Factor of Safety. The results of some of these analyses, presented in Table II, indicate little change in stability from as-built conditions. This is due primarily to the small gains in foundation clay shear strength. Assessments of present and future stability were therefore based substantially on judgement. Raising the crest to maintain freeboard was still considered a calculated risk that was necessarily taken to continue rail traffic over the Causeway.

Caution and continual monitoring of embankment performance were recommended, and contingency plans for adding fill to the berms were developed in case settlement rates became excessive.

In two areas, each about 1/2 mile long, settlement rates have recently been on the order of 1 to 1-1/2 ft. per year which is 2 to 4 times the "normal". Both areas have been identified as probably having a locally weaker

salt stratum. Inclinometers recently installed offshore have shown there to be significant, ongoing, lateral displacements of soft clay below the salt, nearly 30 years after construction. The question of the future performance of these areas and the possible development of other similar areas remains a calculated risk.

CONTINUING CALCULATED RISKS

Today, many uncertainties and limitations still exist which make assessments of Causeway stability, a continued calculated risk. Principal contributing factors are:

1. Likely variations in foundation strata conditions from those assumed based on the limited number of borings made along the 12-1/2 mile long embankment.
2. The presence of the Glauber's Salt, a brittle yet ductile material, that is heterogeneous with depth and lateral extent. Its strength may change with time due to deformation from consolidation of the underlying clays.
3. Very slow consolidation and strength gain in the clays below the Glauber's Salt.
4. Lack of precision in the Factor of Safety calculation due to inaccuracy in determining soil parameters and soil and fill stratification.
5. Inability to adequately accommodate the salt layer in current stability analyses due to its strain incompatibility with the fill and foundation clays.
6. Inability to analyze more than a few representative cross-sections along the 12-1/2 mile long embankment due to cost and time constraints.

CONCLUSIONS

Original design expectations on lake levels and consolidation of the foundation clays below the salt stratum have not come to fruition. Consequently, the recent rise of the Great Salt Lake to historic levels and the need to add fill to the Causeway crest have created a unique situation wherein the end-of-construction was not necessarily the critical time for stability.

It was anticipated that Factors of Safety would again be close to the 1.0 adopted in design. The comparative approach to stability assessments, adopted for evaluations of current conditions and recent elevated lake levels, indicated 10 to 20 percent greater stability than at the end-of-construction where the Causeway is founded on soft clay.

However, embankment stability remains an intractable problem for more than half its length where the Causeway is founded on interbedded salt above soft clays, due to problems of salt/clay strain incompatibility and salt stratum heterogeneity and probable changes since construction. Therefore, the results of analyses made for the no-salt West Side were used for insight in stability considerations. However, the substantial amount of engineering judgement required in assessing stability continue to make such evaluations calculated risks.

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